1 Introduction: Science, STEM, and Society

Why Do You Want to be a Scientist?

I have taught a graduate seminar on Broader Impacts since 2006. On the first day, I open the class with the simple question above. It appears from the quizzical looks on many students' faces that they have never been asked this question, or even considered it for themselves. This notable lack of self-reflection and awareness is despite the fact that this fundamental question defines who they are and what they are studying to be. As a student, I likewise never considered this question or its significance.

Now that I have asked this question of many students, I can predict two kinds of responses. In the first, the student describes their innate curiosity and how they want to understand the natural world. In the second, the student describes how they want to make the world a better place, or to have a positive impact on society. This latter response is consistent with the notion of social responsibility (Inset 1.1). It also becomes clear after several responses that some of the students are interested in both – they have innate curiosity, as well as a desire to find meaning in what they will do with their lives.

Social responsibility

Ethical framework in which individuals and organizations are expected to act for the overall benefit of society.

NSF's Broader Impacts exemplify the social responsibility of science.

Inset 1.1

I then ask the students why they are taking this course. They typically respond that they are interested in the topics, or some say that they are taking it to make them more successful with grants, particularly from NSF. Some students are taking the class despite the skepticism of their major professors. Many of their mentors were brought up in an ivory-tower culture devoid of Broader Impacts. As such, they typically lack an appreciation of the importance of societal benefit in their research. Thankfully, the culture is changing.

On an upbeat note, as exemplified by the students in my class, most of the next generation are far more accepting of the philosophical

Cambridge University Press
978-1-108-42172-0 — Broader Impacts of Science on Society
Bruce J. MacFadden
Excerpt
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justification for why they are training to be scientists. NSF's Broader Impacts are therefore an easier sell to the next generation, and this bodes well for the future. Social responsibility and societal benefit are not concepts particular to the United States, but they are part of the ethical framework in other countries that support basic research (e.g., Rajput, 2018).

Introduction

> New frontiers of the mind are before us, and if they are pioneered with the same vision, boldness, and drive with which we have waged this war we can create a fuller and more fruitful employment and a fuller and more fruitful life.
>
> Franklin D. Roosevelt, 17 November 1944 (in Bush, 1945)

This chapter provides an overview of why science, and in a broader context STEM, are of fundamental importance to the progress of nations and their citizens in the twenty-first century. We will return to some of the topics in subsequent chapters, but here they provide the foundation and rationale for the fundamental importance of science and STEM in society. The focus of this chapter is the context of science and STEM in the United States, primarily during the second half of the twentieth century and beginning of the twenty-first century. Nevertheless, in a globally connected world, much of what is described here also pertains to other STEM-enabled countries as well.

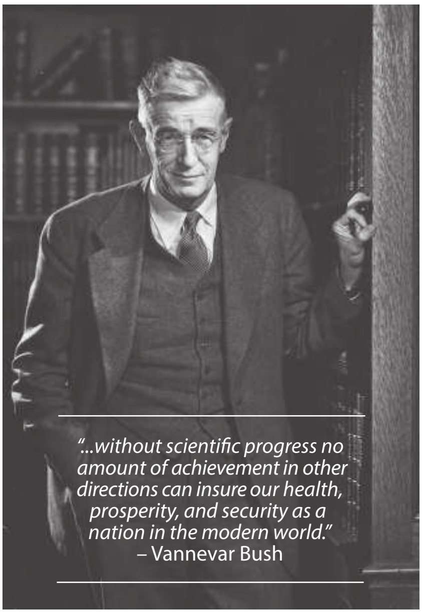
Most of this chapter is guided by a 1945 report titled *Science: The Endless Frontier*. It was transmitted to US President Franklin D. Roosevelt by Vannevar Bush (1945), who at the time was Director of the Office of Scientific Research and Development. Much of the context of that report relates to the enormous impact that science had on the development of technology and practical applications during World War II. Several quotes from this report presented in the following exemplify the vision and framework for the next half-century. Although the acronym STEM had not yet been invented, this report charted the course for the development of science, technology, engineering, and mathematics in the United States after World War II. In the early part of the twenty-first century, Bush's vision and recommendations still have relevance (Pielke, 2010).

This chapter concludes with a discussion of politics and science in the twenty-first century. Bush understood that for science to be successful, the federal government would need to invest in this enormous enterprise. A corollary is that oversight and accountability would be important. It is unclear whether Bush, or any other learned person in the middle of the twentieth century, could have foreseen the extent to which science and STEM has been "politicized" in modern society. This is exemplified by politicians taking stands on "hot-button" topics such as evolution, climate change (*sensu*

Leshner, 2010), and federal versus state standards dictating how STEM should be taught in K–12 schools.

Value of Science and STEM in Society

The rationale for science that Vannevar Bush (Inset 1.2; Carnegie Institution of Washington photo) envisioned in the middle of the twentieth century still holds true in the context of how STEM is of value in service to modern society. His words in 1945 were heavily influenced by the context of military superiority during World War II. This is not surprising, given the fact that many important innovations, emerging fields, and new ways of doing science and technology occurred during this time, funded by investments from government and the private sector. To name just a few: radar (and sonar), computers, and airplanes all saw major leaps forward during World War II and thereafter were put to use for the benefit of society. The field of operations research largely started with British and American scientists during this time. For example, Patrick Blackett (who later received the Nobel Prize) used applied mathematics to optimize the configuration of anti-aircraft installations defending London, or the size of merchant ship convoys crossing the North Atlantic to defend against German U-boat attacks (Budiansky, 2013). The Atomic Age, of huge societal impact – both positive and negative – also started during this time. Many of the scientists of the Atomic Age also understood the importance of public understanding of science and technology for societal benefit – for example, in 1969 the physicist Frank Oppenheimer (brother of Robert J. Oppenheimer) founded the Exploratorium science center in San Francisco (Exploratorium, 2018).



Inset 1.2

It is also understood that science is important during peacetime. In addition to the advances in knowledge, innovation, and scientific capital, in modern society STEM employs 5–10 percent of the workforce in the United States (US Department of Commerce, 2011). Although not a large percentage of the overall workforce, these jobs (Fig. 1.1) are important for economic progress and world leadership. Many of these jobs require considerable levels of education and, in turn, reward workers in careers with appropriate levels of compensation. Moreover, the rate of job growth in the United States is greater in STEM than in non-STEM fields (Fig. 1.2).

> Science is a catalyst for health information technology, agriculture, and energy, driving the national economy; it deserves to be valued as such.
>
> Barbara Schaal, AAAS President (2017)

Fig. 1.1 Word cloud of STEM job code names (compiled from Noonan, 2017).

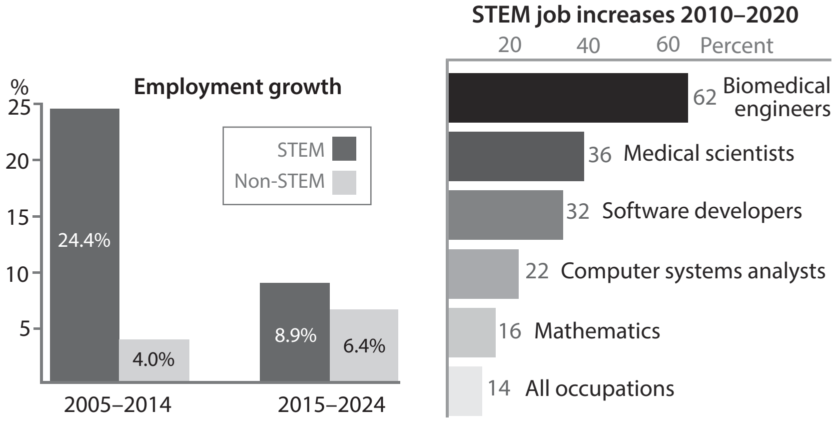


Fig. 1.2 Left: Projected employment growth in STEM versus non-STEM fields in the early twenty-first century (Noonan, 2017). Right: Projected increases in STEM jobs, by category, 2010–2020 (US Department of Education, 2017).

Since the middle of the twentieth century, a sense of importance has emerged among the world's industrialized nations about their dominance, or position, with regard to science and technology. Bush (1945) advocated that the United States should lead in this regard, rather than play catch-up from innovations produced by other nations. In a modern context, China is undergoing reform of its government's science and technology infrastructure with a vision to be a world leader rather than being in a position of technological catch-up. Government, industry, and academic leaders have come together to formulate a national research and development (R&D) agenda with a goal of improving China's position in science and technology through the middle of the twenty-first century (Cao & Suttmeier, 2017). China's recent investment in R&D is impressive and on the rise. China is ranked second behind the United States in overall R&D investment, but significant gains are being seen from the former. Whereas in 2012 China spent 34 percent as much as the United States on R&D, in 2017 it was closer to 45 percent. Thus, in China funding for this sector of the economy has risen significantly, by 12.3 percent (to the equivalent of $254 billion) in 2017 over the previous year, and it is likely to continue to rise (Normile, 2018).

In order to be a world leader in science and technology, nations need to invest in creative work that increases knowledge. One metric of this investment is the research expenditure of the government and private sectors as a percentage of the gross domestic product (GDP). Using this metric, at 2.7 percent of its GDP in 2013, the United States ranks ninth (China is fourteenth) of all countries for which data are available (Fig. 1.3), after Korea, Israel, Japan, Sweden, Finland, Denmark, Austria, and Germany (World Bank, 2017).

The world's population is projected to exceed nine billion by 2050 (Jarvis, 2017). At its current rate of growth, the US population is estimated to be 436 million by 2050 (Passel & Cohn, 2008); which represents a 34 percent increase from 325 million in 2017 (US Census Bureau, 2017a). This inexorable growth of the human species on

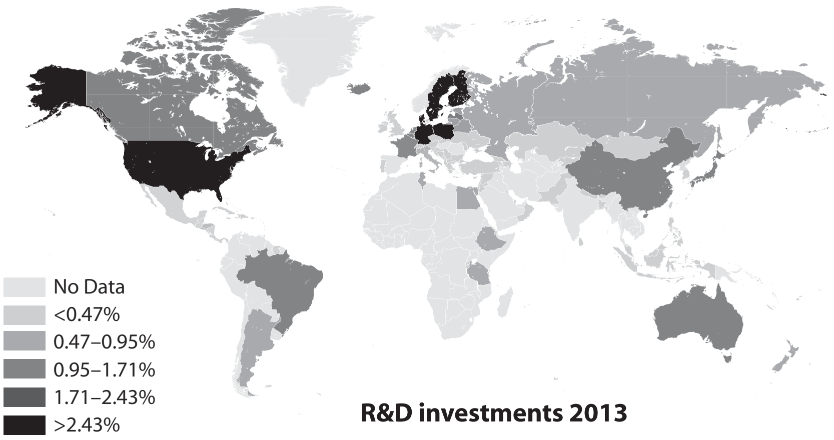


Fig. 1.3 Expenditures for R&D as a percentage of the GDP for 2013, by country (World Bank, 2017).

Earth further underscores the importance of STEM to address fundamentally important issues, including national security, health, food, water, energy, environment, and sustainability in the twenty-first century.

Basic Science and "Useless Knowledge"

> Basic research leads to new knowledge. It provides scientific capital. It creates the fund from which the practical applications of knowledge must be drawn.
>
> Bush (1945)

It is easy to understand why scientific and technological innovation are important when there is direct, or perceived, benefit for society. But how can we rationalize investment in the production of knowledge for its own sake without immediate application? This question has existed ever since governments have invested in science. It is of particular importance in organizations, whether they be in government or the private sector, that are not mission-based, that is ones that support what might be called basic research (Bush, 1945; Pielke, 2010). "Basic research" is done for science's sake because it is potentially novel, innovative, and leads to new discoveries. The same is also true for much of the research in mathematics. Unlike basic science and mathematics, within the context of STEM, technology and engineering, as well as medical research, are typically identified with a problem to be solved or a direct application in mind.

Three-quarters of a century ago, Bush understood and supported the idea of basic research as an investment in the infrastructure and knowledge base of the United States. He is not the only high-profile scientist of the middle twentieth century who both understood and advocated for the place of basic science in society. In 1939, Abraham Flexner, who founded the Institute of Advanced Study at Princeton University (and was instrumental in bringing Albert Einstein to the United States), wrote an essay entitled "The usefulness of useless knowledge." In a recent retrospective about Flexner and his essay, Dijkgraaf (2017; see also Tovey, 2017) describes not just how basic science is available for future applications, but also its importance in social and cultural change. As an example, without quantum mechanics there would be no computers, fiber-optic telecommunications, or smartphones (Orzel, 2015). Lasers were initially developed a half-century ago primarily within a framework of basic research (Cartlidge, 2018), but have subsequently been translated into many important applications that have benefitted society and impacted the modern world.

In Chapter 2 we will learn in more detail about the beginning of the US National Science Foundation (NSF) in 1950, which largely resulted from the advocacy of Vannevar Bush. He and NSF's founders understood that science needed to be done for a variety of reasons that would impact both basic knowledge as well as practical applications. It is in the realm of basic science that the seeds of NSF's Broader

Impacts were sowed. Almost since the beginning of NSF, and particularly in a time of increased skepticism about science and STEM in society, there has been tension between "ivory tower" science and government oversight and accountability. The extent to which society values basic research is at the core of the debate about return on investment of government funds.

The debate about the value of pure science hits close to home because my field is paleontology, the study of fossils and what they tell us about evolution and the Earth during the past 4.6 billion years of "Deep Time" (McPhee, 1981). There are some notable exceptions, such as the new field of conservation paleobiology (Dietl & Flessa, 2011; 2018), in which studies of past ecosystem changes can inform modern policies about conservation. Otherwise, paleontology does not have much direct, or immediate, practical application. Nevertheless, the study of fossils informs relevant topics such as evolution and climate change. In addition, as many kids will tell you, dinosaurs are cool, and these extinct creatures therefore provide a charismatic gateway for STEM engagement in the twenty-first century. The direct societal benefit, if not practical application, of paleontology is that it potentially engages the next generation of STEM learners and hopefully opens their minds to discovery.

Diversity, Workforce, and STEM

> Studies clearly show that there are talented individuals in every part of the population, but with few exceptions, those without the means of buying higher education go without it. If ability, and not the circumstance of family fortune, determines who shall receive higher education in science, then we shall be assured of constantly improving quality at every level of scientific activity.
>
> Bush (1945)

Between 5 and 10 percent of the workforce in the United States, or about 8–9 million people in 2017, are employed in STEM jobs. It is clear that the key to successfully developing this workforce is to include the diversity represented in the United States, including men, women, and underrepresented minorities. A goal for this strategy should be that the STEM workforce mirrors the diversity of the United States as a whole. While this is a laudable and appropriate goal with regard to social responsibility, it is not the reality today. The STEM workforce in the United States, particularly in senior positions and higher-paying jobs, is disproportionately represented by white males.

The reasons underlying the lack of diversity within the STEM workforce in the United States are complex. This disparity is currently not being effectively addressed in order to achieve full equality. The two most affected groups in this regard include women and underrepresented minorities. Although women oftentimes are interested in STEM at an early age, for complex reasons they progressively lose interest both in STEM and in related careers. For those females who persevere past adolescence, the road to a career in STEM is no less easy (Handelsman et al., 2005; McNutt,

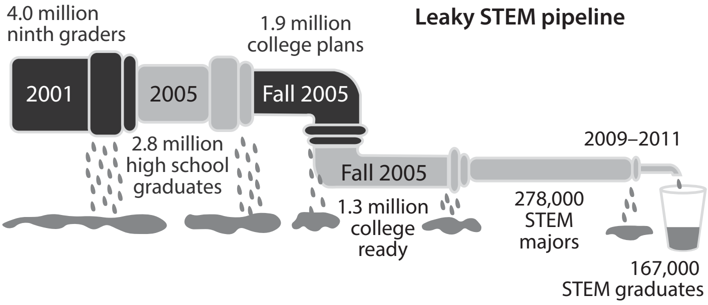


Fig. 1.4 The STEM leaky pipeline showing loss of women, minorities, and low-income students during different phases of the educational and workforce system (modified from Dubois, 2014).

2013). This attrition has been termed the “leaky pipeline” (Fig. 1.4), or the progressive loss of women and underrepresented minorities “up the ladder” and in more senior positions in STEM (Blickenstaff, 2005; Dubois, 2014). This loss is not just restricted to the United States, but also exists in other countries (Professionals Australia, 2017; Resmini, 2016). As an example of the disparity in the workforce, women researchers in STEM vary from about 40 percent in China to a low of 20 percent in other parts of Asia and the eastern Pacific; the world average is 30 percent. In the United States women comprise half of the national workforce, but only one-quarter are employed in STEM fields (Landivar, 2013; Wu, 2016).

In addition to the disparity with women in STEM, minorities including Hispanics and Latinxs, African-Americans, and Native Americans are likewise poorly represented relative to their percentages in the US population. Although these groups collectively represent nearly 30 percent of the US population, they comprise only 9 percent of the STEM workforce (Ferrini-Mundy, 2013). This situation has not improved significantly since the turn of the twenty-first century despite multifaceted efforts toward equality and inclusion (Hrabowski, 2011). Interest in STEM among the next generation of African-American and Hispanic youth has actually declined since 2001. Without effective interventions, the outlook for future engagement in the STEM workforce is likewise not an optimistic scenario (Bidwell, 2015). The reasons for poor participation of these underrepresented minorities in STEM are complex, but relate to a variety of factors including family and social norms, perceived value, lack of relevance, educational achievement, and a dearth of suitable role models in STEM in the United States. In contrast to this lack of increased participation, non-US students, particularly from China and India, represent most of the growth in earned doctorates in STEM in the United States in the twenty-first century. Many of these graduates, however, return to their home countries and therefore do not contribute to the STEM workforce in the United States (Hrabowski, 2011). Another related problem with the current STEM workforce is the disparity between supply and demand. Thus, in some sectors such as biology, the supply of PhDs greatly outnumbers the available jobs; in fact, there is an order of magnitude difference

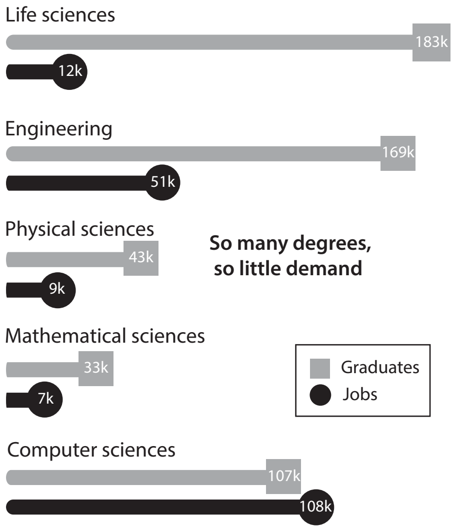


Fig. 1.5 Disparity between the supply of PhDs and demand for jobs within different STEM sectors (modified from Lohr, 2017).

between PhDs produced and available jobs (Lohr, 2017; Fig. 1.5). This hypercompetitive situation is exacerbated if the job search is focused on tenure-track positions in academia. Within the biomedical sciences, only 10 percent of trainees in the United States obtain the coveted tenure-track job five years after completing the PhD (Blank et al., 2017). In contrast, however, in computer science the supply of new PhDs roughly equals the supply of jobs. In a recent book, *The Graduate School Mess*, Cassuto (2016) analyzes this problem from the point of view of the challenging job market for PhDs in the humanities, but many of his observations and conclusions also pertain to certain sectors of STEM.

As Bush (1945) advocated, the diversity of minds, ideas, and human perspectives are fundamental to the success of the United States as a leader in scientific and technological innovation and as a player in the global market. From a pragmatic point of view, the majority of our future economic growth is linked to STEM. Until a workforce exists that more closely mirrors the demographics of the US population, and is optimized for supply and demand, then we will not have fulfilled our social responsibility or realize the economic benefits of diverse participation in STEM.

On to the Twenty-First Century

Globally Connected STEM

The twentieth century witnessed an unrivaled expansion of international conflicts, particularly during the two World Wars. During peacetime, international cooperation, diplomacy, and scientific collaboration were unprecedented. During the late twentieth century and the beginning of the twenty-first century, a globally connected STEM community has greatly benefitted from the technological innovations provided by cyberinfrastructure, most notably including electronic communication (email), social

Global competence

- International awareness
- Appreciation of cultural diversity
- Proficiency in foreign languages
- Competitive skills

Twenty-first-century skills

- Learning and innovation
- Digital literacy
- Career and life

Inset 1.3

media, and other cyberenabled modes of communication such as videoconferencing. These connections have done much to break down barriers of geography, time, and politics. Thus, STEM today involves international collaboration at an unprecedented rate. As an example, the number of peer-reviewed articles produced globally with authors from different countries has doubled since 1990 (Bollyky & Bollyky, 2012). This globally connected community also requires, and in turn benefits from, investments in political, economic, and social development made by both governments and the private sector.

Globally connected STEM also requires an expanded set of competencies and skills in order to optimize success in the twenty-first century (NEA, 2017; P21, 2017; Inset 1.3). The application of these competencies is also relevant to other segments of society, including business and government. Of relevance here, the competencies focus on international and cultural awareness and diversity (NEA, 2017). Despite the notion that English is the de facto language of science (van Weijen, 2012), global competencies should transcend the research and development infrastructure of STEM to include other languages as well. Only about 7 percent of the world's population of 7.5 billion people speak English as their native language. If percentages were a primary factor, then the language of science should be either Chinese (19 percent, 1.4 billion people) or Hindi-Urdu (8 percent, 588 million people), although English is spoken in more than 100 countries (Chinese is spoken in 33 countries; Noack & Gamio, 2015).

A generation ago, PhD students in the United States were required to demonstrate proficiency in one, or even two, foreign languages as part of their degree requirements. (I had French and German, but should have taken just Spanish instead.) Despite the other requirements placed on demanding PhD programs, it is beneficial for students actively involved in international research to communicate in the language of the collaborating country. In the twenty-first century, foreign-language competency for PhD students in US universities is not mandatory, although perhaps this requirement should be reinstated.

I was once invited to become a member of a PhD committee for a student conducting research in South America. He would be doing field work in rural areas, and Spanish would have been very helpful, and also shown the local scientists that he cared enough to learn the native language. I insisted that if I were to serve on his committee, the student would have to demonstrate proficiency in Spanish. His major professor said it was not necessary. I disagreed and the outcome was that I did not serve on this committee, which was fine with me.

In addition to global competence, leaders from diverse segments of society have realized the importance of what are now called twenty-first-century skills (P21, 2017; Trilling & Fadel, 2012; Inset 1.3). While much literature has been devoted to these